DEVELOPMENT AND QUALIFICATION OF PASSIVE ACTIVE MULTIJUNCTION (PAM) LAUNCHER FOR LHCD SYSTEM OF ADITYA -UPGRADE TOKAMAK

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Abstract

A Passive Active Multijunction (PAM) launcher is designed and developed to deliver RF power up to 250 kW for 1 second. The launcher would be commissioned on the ADITYA-U tokamak. The PAM launcher has many advantages over the grill launcher such as exhibiting a lower reflection coefficient at the plasma densities close to its corresponding cut-off density. A few prototype components are fabricated to establish and benchmark the fabrication processes before proceeding with the actual fabrication. Two types of techniques are employed to realize the PAM launcher. The first one is based mainly on the machining of components from a solid block whereas the other one employs plate-fit technique. The paper presents a representative case for both the techniques. The fabrication details of the tapered divider (single block machining technique) and step phase shifter (plate-fit technique) are presented. The components are further qualified with respect to their critical properties like material testing, material defect, dimensions, profiles, surface finish et cetera.

1. INTRODUCTION

The upgradation of the ADITYA Tokamak provides an opportunity to design and develop a new type of lower hybrid wave launcher on it. Unlike the grill launcher which was used earlier [1], a Passive Active Multijunction (PAM) launcher is designed [2] and will be fabricated to deliver up to 250 kW of RF power in to the plasma at 3.7 GHz. The PAM launcher increases the coupling of the RF power to the plasma at plasma densities close to their corresponding cut off density.

The PAM launcher is designed to launch $N_{\parallel}$ of 2.25 ± 0.75 considering the wave accessibility condition [3] for the ADITYA-U tokamak. The launcher has 2 modules in the toroidal direction and 3 modules in the poloidal direction, with each module having two active and two passive waveguides. The design consists of 4 parts namely PAM Multijunction, tapered divider, mode convertor and vacuum window. The PAM Multijunction consists of the active and passive waveguides and step phase shifters to provide appropriate phasing which would steer the RF waves in the desired direction. The tapered divider section facilitates the translation of the output dimensions of the mode convertor to the input dimensions of the PAM launcher. The mode convertor is used to convert the input TE_{10} mode to TE_{30} mode to feed the 3 poloidal modules. The details of the complete launcher design and its critical dimensions are reported in [2]. Fig. 1 shows the 3D structure of the complete PAM launcher.

There exist various fabrication techniques to realize the PAM launcher. Two simplest techniques which may be employed in fabrication of the PAM launcher are machining of the component from a single thick block material and plate-fit mechanism. These two techniques are tried out for two PAM launchers component, namely tapered divider and step phase shifter. The paper discusses the development and dimensional qualification of the tapered divider in Section 2 while Section 3 describes the development and qualification of a prototype 90° step phase shifter. Section 4 concludes the paper.

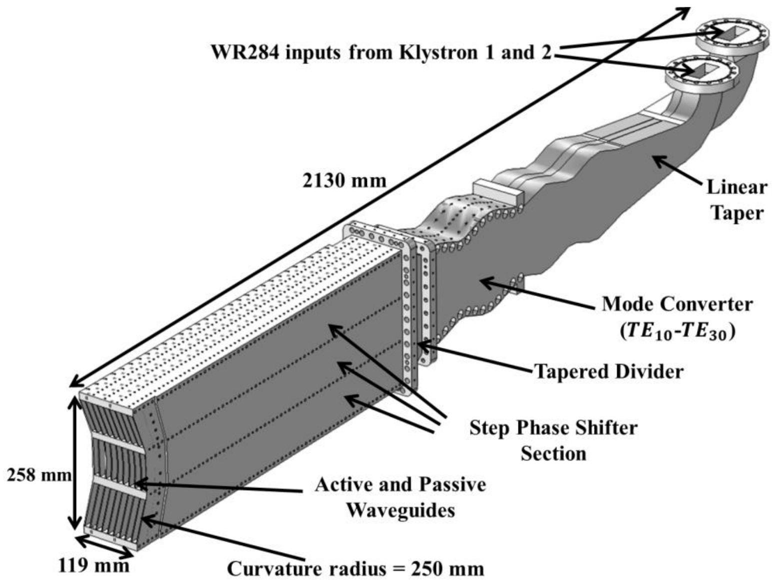


FIG. 1. A 3D structure of the complete Passive Active Multijunction (PAM) launcher.

2. DEVELOPMENT OF THE TAPERED DIVIDER

The Tapered Divider was fabricated using Stainless Steel SS304L material because of its non-magnetic properties and high mechanical strength. Various processes and protocols are employed for the development of the tapered divider such as material testing, sizing, Vertical Machining Centre (VMC) machining, Wire Cutting, Ultrasound cleaning, Grinding, Electropolishing et cetera. This section discusses the development of a Tapered Divider which employs these procedures.

The SS304L raw material, which would be used for the machining, was tested to identify any defects or flaws in the material. The material was also tested for its chemical composition and mechanical properties. An InterGranular Corrosion (IGC) Practice 'E' test was carried out as per the American Society for Testing and Materials (ASTM), A262-2015. The tests confirmed that there were no IGC-fissures or cracks in the material. An Ultrasonic test confirmed that the raw material was free from any objectionable flaw. The chemical composition of the material was determined using the Spectroscopy-OES method and is as shown in Table 1. It can be inferred from Table 1 that the chemical composition of the raw material conforms the standards of SS304L.

TABLE 1. CHEMICAL COMPOSITION OF THE SS304L RAW MATERIAL

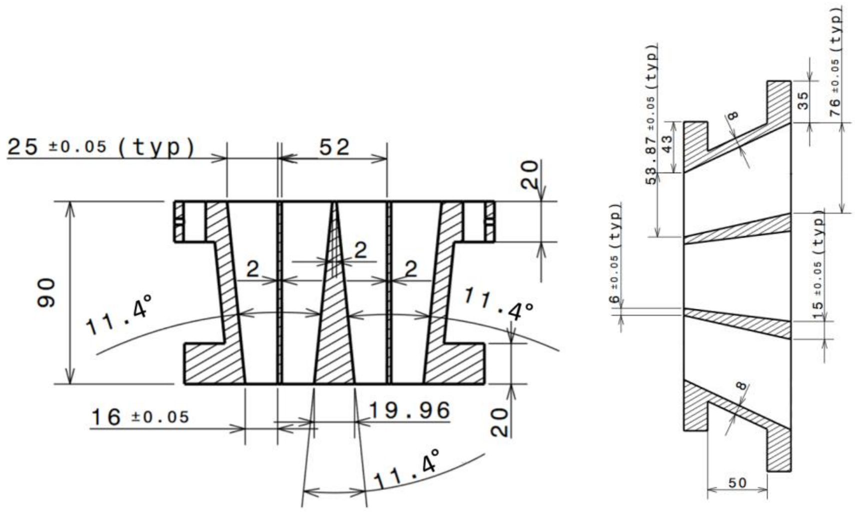
	Percentage obtained	Standard Percentage Value
Carbon	0.025	0.03 max
Silicon	0.226	0.75 max
Manganese	1.700	2.00 max
Phosphorus	0.037	0.045 max
Sulphur	0.014	0.030 max
Chromium	18.360	18.0-20.0
Nickel	8.420	8.0-12.0

A Rockwell hardness test and the tensile strength test were performed to determine the mechanical properties of the raw material. Table 2 shows the detailed results of the tests performed. Also, the results confirm that the material is fit to be used for fabrication.

TABLE 2. MECHANICAL PROPERTIES OF THE SS304L RAW MATERIAL

Property	Values obtained	Standard Values
0.2% Proof Stress	275.54 MPa	170 MPa min
Ultimate tensile stress	565.55 MPa	485 MPa min
% Elongation	61	40 min
Hardness in HRBW	75	92 max

The tapered divider is a simple section with 12 tapered rectangular waveguides transforming the 6 outputs (53.87 mm × 32 mm) of the mode converters to the 12 inputs of the PAM launcher (76 mm × 25 mm). The input of the tapered divider has 12 rectangular pockets (53.87 mm × 16 mm) thereby dividing the 6 outputs of the mode converters into 12. Thus, the tapered divider has an input flange outer dimension of 259.6 mm × 148 mm with 12 pockets (53.87 mm × 16 mm) and an output flange outer dimension of 382 mm × 158 mm. The tapered divider has a final outer dimension of 328 mm × 158 mm × 90 mm. This dimension also incorporates the thickness of the flanges as they are machined from the same block. Fig. 2 (a) shows the top view and Fig. 2 (b) shows the side view of the tapered divider with all the critical dimensions and the desired tolerances of ±50 microns. The tapered angle required to be maintained to obtain the desired dimensions is 11.4°.



(a) *(b)*

FIG. 2. (a) Top View of the Tapered Divider, (b) Side View of the Tapered Divider.

A solid block of dimension 340 mm x 170 mm x 100 mm was initially shaped to machine flanges at the ends using VMC machining. Twelve guide holes each of 5 mm diameter were made at the rectangular pocket centres to aid the wire cut machining process to be employed later. Also, 26 holes (for M10 threading) were made in the input flange at the periphery as shown in Fig. 3 (a) while 34 through holes of 11 mm diameter were made in the output flange as shown in Fig. 3 (b). Each flange has 8 additional holes for counter dowels. The dowel holes are required to match the input and output rectangular pockets with the output of the mode convertors and the input of the PAM launcher respectively. These holes are at the periphery of the flanges. Fig. 3 (c) shows the solid block after the VMC machining.

(a) (b) (c)

FIG. 3. (a) Input flange of the Tapered Divider, (b) Output flange of the Tapered Divider, (c) Solid Block Tapered Divider after VMC machining.

The pockets are cut by employing a 5 Axis Wire Electrical Discharge Machining (EDM). A 0.3 mm thin, electrically-charged EDM wire used acted as one electrode while the solid block being cut formed the second electrode. An electrical discharge between the wire and the block results in sparks which eventually cuts the block. The block was immersed in deionized water during the process which helps in flushing away the debris. The most critical part was to make the inclined rectangular pocket in the block as the EDM wire cuts the metal in a vertical direction. The block was held with a precise tilt so as to allow the cutting of the rectangular pockets at the desired angle. As the inner dimensions of the pocket vary linearly in both directions, therefore the challenge was to set the precise tilting angle under various configurations. All rectangular inner pockets are separated with 2 mm thick wall. Fig. 4 shows the tapered divider after the EDM wire cutting process.

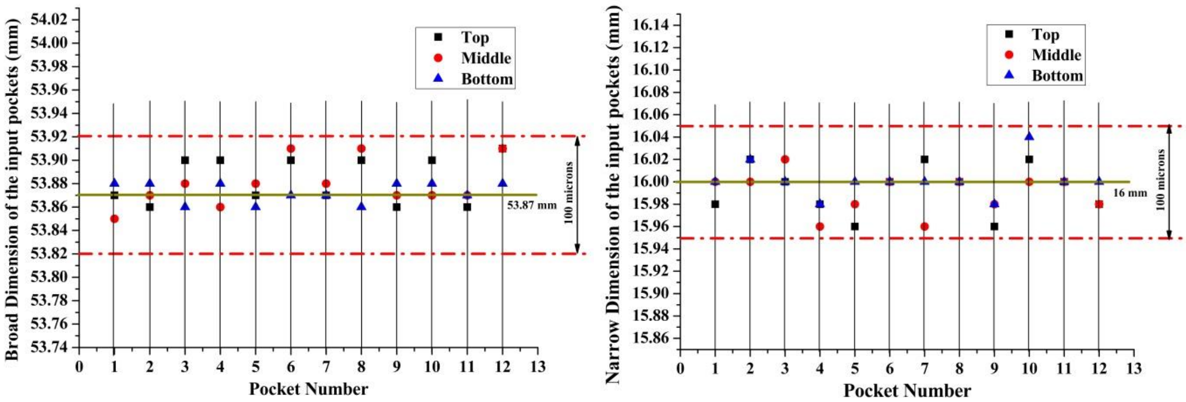
FIG. 4. Tapered Divider after EDM Wire Cutting process.

Ultrasound cleaning method was used to remove any dirt, oil, machinery coolant et cetera from the surface of the divider. The inner surface of the tapered divider and its end surfaces which are to be connected to other components require a surface finish of 3 delta which was obtained after electropolishing.

A dimensional qualification of the tapered divider was carried out as shown in Fig. 5. The most critical dimensions of the divider are the 12 rectangular pocket cross-sections each at the input and the output of the divider. Each pocket cross-section of the tapered divider was measured at three locations (top, middle and bottom of the pocket). The 12 input pockets of the tapered divider have a designed cross-section value of 53.87 mm × 16 mm. The labelling of the input pockets for measurements runs from left to right and top to bottom. Fig. 6 (a) and Fig. 6 (b) illustrates that all the broad and the narrow dimensions respectively measured for all the input pockets at the three locations are well within the tolerance limits of ±50 microns.

(a) *(b)* *(c)* *(d)*

FIG. 5. Measurement photographs of (a) Broad dimension of the input pocket, (b) Narrow dimension of the input pocket, (c) Broad dimension of the output pocket and (d) Narrow dimension of the output pocket.



(a) *(b)*

FIG. 6. (a) Measured broad dimension of the input pocket, (b) Measured narrow dimension of the input pocket.

The designed cross-sectional dimension of the output pockets is 76 mm × 25 mm and similar measurements were carried out on the output flange pockets and the results obtained are within the tolerance limits.

3. DEVELOPMENT OF PROTOTYPE STEP PHASE SHIFTER

A prototype 90° step phase shifter has been developed to benchmark the phase shifter section of the PAM launcher. The design and inner profile of the step phase shifter is reported in [4]. The schematics shown in Fig. 7 and Fig. 8 illustrate the inner profile of the step phase shifter and the covering top plate respectively along with some critical dimensions.

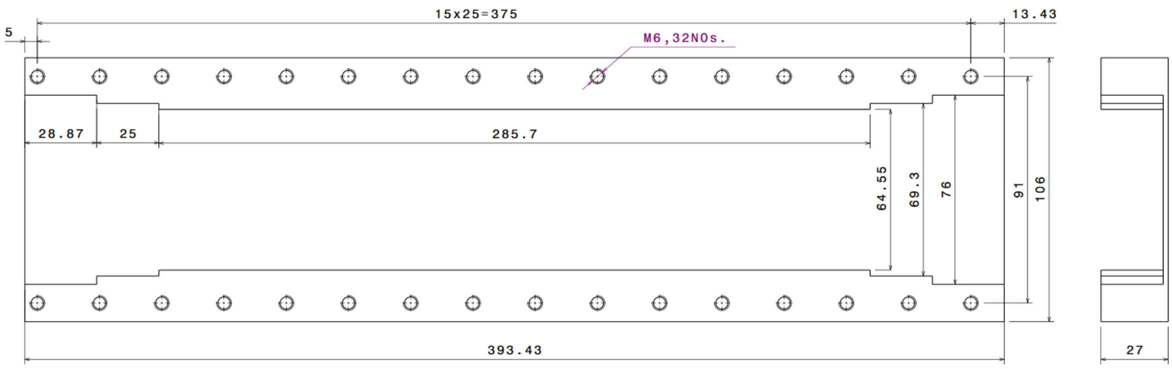


FIG. 7. Profile plate schematic illustrating the inner profile of the step phase shifter.

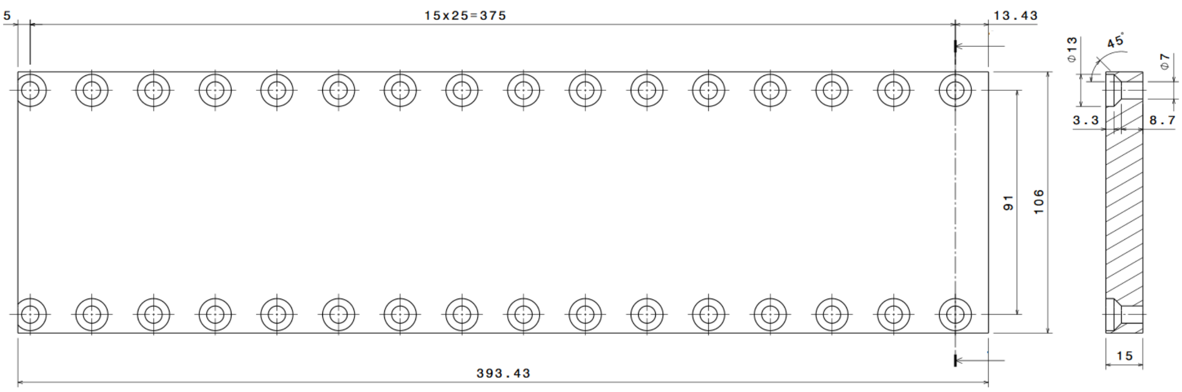


FIG. 8. Covering plate schematic of the step phase shifter.

The major dimension of its inner profile is 76 mm × 25 mm × 393.43 mm. The critical dimensions of the profile are the steps a_1 = 76 mm, a_2 = 69.3 mm, a_3 = 64.55 mm, b = 25 mm and their corresponding lengths. Thus, taking into account the plate thickness and fabrication requirements, two blocks of dimensions 120 mm × 35 mm × 420 mm and 120 mm × 20 mm × 420 mm were used to employ the plate-fit technique in step phase shifter. The material used for its development is same as the one used for the tapered divider and conforms to the standards with respect to the material testing and defects.

A thick plate (here 35 mm plate) is used to fabricate a C-shape section in which the step phase shifter profile is machined using the VMC machining technique. A total of 32 holes are made in the periphery which were later threaded for bolting using M6 bolts. The final thickness of the profiled plate is 27 mm. The machine cutting tool is circular and results in a curve of radius 5 mm at the corners of the steps instead of sharp edges. However, the effect of such curvature is studied with respect to its RF performance and is found to be insignificant. The thin plate (here 20 mm plate) is used as the covering plate and is surface finished on the VMC machine. The final thickness of the covering plate is 15 mm. Holes are made in the covering plate to match the ones made in the profile plate. Both the plates are subjected to Ultrasound cleaning and electropolishing to obtain the required surface finish of 3 delta. The whole assembly is formed by nut-bolting the profile and the covering plate. Fig. 9 shows the fabricated profile plate while Fig. 10 shows the fabricated covering plate.

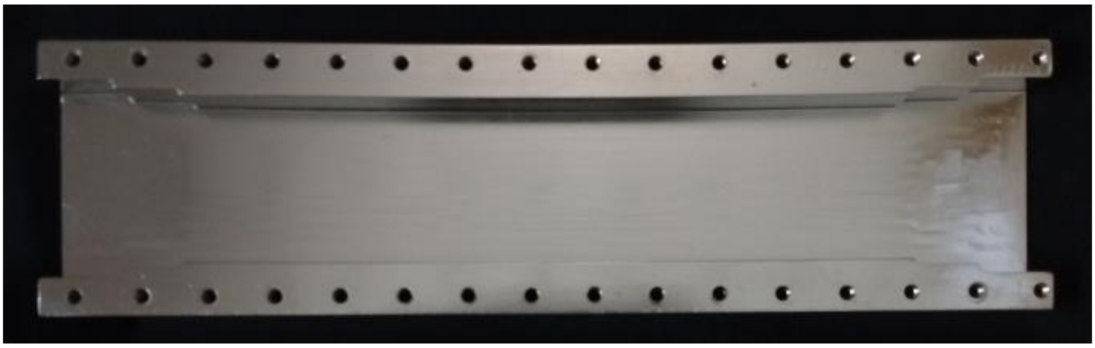


FIG. 9. Fabricated Profile plate of the step phase shifter.

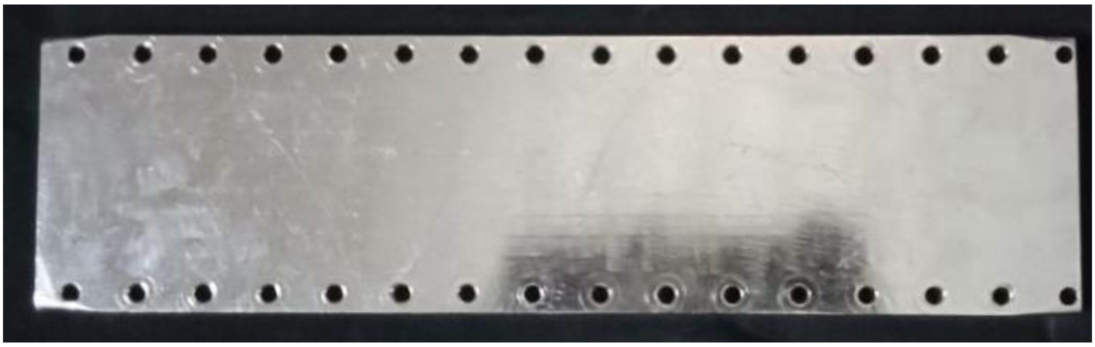
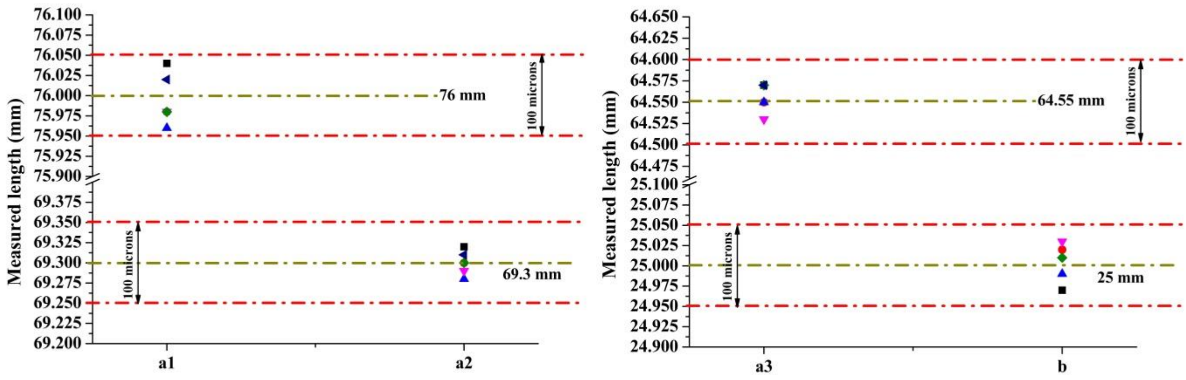


FIG. 10. Fabricated Covering plate of the step phase shifter.

The step phase shifter is symmetrical in nature and has 2 steps of width a_1, 2 steps of width a_2 and one step of width a_3 which can be seen in Fig. 7. The depth of the phase shifter is 25 mm throughout. The widths a_1 and a_2 were measured at 3 locations per step resulting in a total of 6 measure points each. The width a_3 and depth b were measured at 6 different positions each. Fig. 11 confirms that the measurements of widths a_1 and a_2 (a) and width a_3 and depth b (b) are within the acceptable tolerance of ±50 microns. A simple comparison of the mean of the measured values and the designed value is shown in Table 3.



(a) *(b)*

FIG. 11. (a) Measured values of a_1 and a_2, (b) Measured values of a_3 and b.

TABLE 3. MEASURED DIMENSIONS OF THE PROTOTYPE STEP PHASE SHIFTER

	Mean of the Measured Values	Designed Values
a_1	75.993 mm	76 mm
a_2	69.3 mm	69.3 mm
a_3	64.556 mm	64.55 mm
b	25.004 mm	25 mm

4. CONCLUSION AND FUTURE SCOPE

A tapered divider and a step phase shifter is developed and qualified using various testing, fabrication and measurement procedures and protocols. Two techniques namely machining out of a single block and plate fitting are used for the fabrication of these components. There is a good agreement between the designed and the fabricated component dimensions. The measurements suggest that these processes can fabricate the designed components within desired tolerances. Thus, the fabrication procedures are identified and benchmarked. The other components of the PAM launcher can thus be fabricated using these techniques with consistent tolerances

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